
COMPUTER-AIDED PROCESS CONTROL SYSTEMS

Control of Combustion Processes in an Internal Combustion Engine by Low-Temperature Plasma

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Abstract—A new method of operation of internal combustion engines enhances power and reduces fuel consumption and exhaust toxicity. Low-temperature plasma control combines working processes of thermal engines and steam machines into a single process.

1. INTRODUCTION

Prevention of air pollution is a vital problem today. Automobile exhaust gases change the atmospheric composition and enhance the concentration of toxic substances to a health-hazard level. This explains the increased requirements imposed on the specific power of internal combustion (IC) engines, fuel consumption rates, and exhaust gases. Therefore, improvement of the fuel combustion process acquires special importance, because power, economic, and ecological indexes of an engine largely depend on and restricted by the properties of this process.

The quality of the combustion process is largely dependent on fuel mixture composition, optimal pre-ignition reactions, and combustion of fuel components in the combustion chamber. To obtain high-quality characteristics of this process, heat must be liberated in time and sufficient quantity under minimal losses at chamber walls. This is not easy to achieve in complicated and constantly changing conditions of engine operation.

Moreover, even the ideal combustion process takes place under conflicting conditions. For example, poor fuel mixtures (with excess air coefficient 1.5–1.6) ensure complete fuel combustion, absence of toxic components, and fuel economy. But it is not possible to ensure stable and complete combustion of such a mixture by traditional methods.

Increased compression ratio, which boosts the combustion process in the initial phase and accelerates the rate of propagation of turbulent flames in the main combustion phase, and the related decrease in combustion chamber sizes, which suppresses the scale of turbulent pulsations and hinders flame front propagation, are also conflicting.

It is also not easy to aid complete liberation of heat under minimal heat transfer from burnt gases to chamber walls and piston head (up to 25% of fuel energy is transferred to the cooling system) and increase the efficiency of conversion of thermochemical energy into mechanical energy.

Our method of controlling the fuel combustion process in an IC engine [1] considerably reduces this conflict in requirements for carburetor engines and diesel engines. The method consists of creating a low-temperature plasma inside the liquid component of the fuel mixture for varying the amount and rate of supply of energy to the plasma channel (streamer) over a wide range and for controlling the stages of thermochemical process via transformation of the plasma energy into mechanical and internal energy of the mixture.

2. THERMOCHEMICAL CONVERSION OF THE WORKING BODY OF IC-ENGINES

Figure 1 shows the combustion chamber of an engine working by the new scheme. Combustion chamber 1 containing fuel mixture 2 carries two insulated electrodes 3 and 4 between which a drop 5 of the liquid component is injected.

First we describe the operation of a carburetor engine, in which distilled water is used as the liquid component.

A high-voltage pulse 6 is fed to electrode 3 at the end of the compression stroke. The spark creates a low-temperature plasma inside drop 5. In the incipient stage, the liquid hinders the expansion of the plasma channel and, consequently, the plasma energy density increases and, consequently, plasma temperature and pressure in the channel rapidly increase. We can approximately assume that the energy liberated in the plasma channel is mostly is used in heating the substances in the discharge channel and expanding the channel. Liquid is somewhat overheated due to rapid heating and high pressure. As a result, part of the liquid component evaporates due to plasma heat, while the other part is split into fine particles by the compression wave in the microvolume, thereby forming a dispersion phase. When the particle fly, the hot mixture is turbulized and additional vapors are formed. Nonvolatized particles are deposited on the chamber internal surface as a film 7 and continue to evaporate, producing vapors 8, whose heat conductivity is less than that of the liquid. Thus the escape of heat through chamber walls is reduced. At the same time, working mixture is intensively heated and ultimately ignited by the compression wave in the chamber. Thus the mixture inflames rapidly, because the new compression waves formed at the first stage of flame propagation move before the flame front, heat and compress the mixture. Mixture heating accelerates chemical reactions, which boost flame propagation. More intensive compression waves are generated from the accelerating front, and the process becomes self-accelerating. Combustion products 9 are captured by vapor 8, which is overheated and creates additional pressure on the piston in the working stroke.

Let us study this process, using a theoretical pV diagram, in which the volume of the mixture in the engine cylinder is plotted along the x -axis and, pressure along the y -axis (Fig. 2).

A fuel-air mixture of volume V_1 under atmospheric pressure p_1 is compressed by the piston along the adiabat da to volume V_2 . In this process, pressure increases to p_2 . A high-voltage pulse

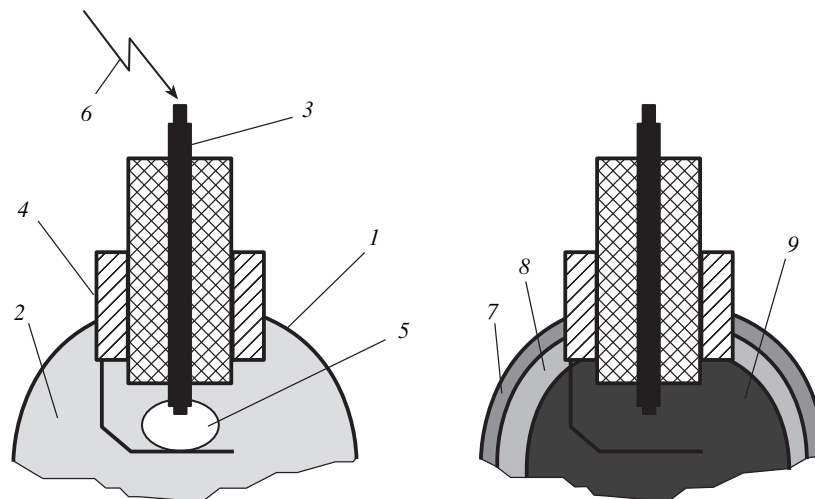


Fig. 1. Engine combustion chamber.

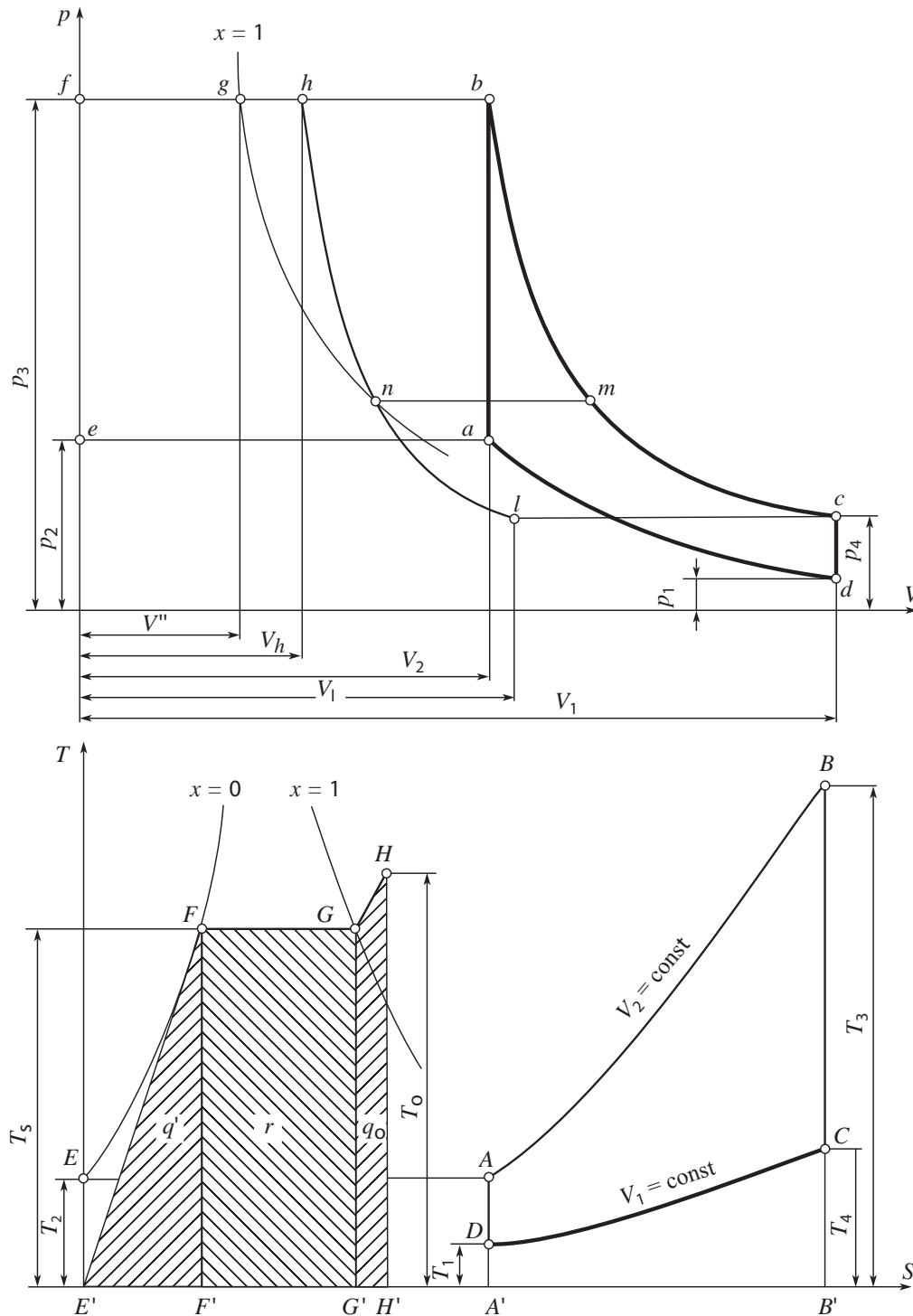
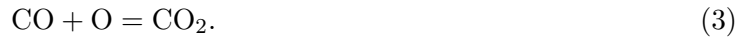


Fig. 2. Working pV and heat Ts diagrams of the state of the engine working body.

is fed to electrode 3 at the point a , which splits the drop into particles, which are deposited as a heat-insulating film on the chamber inner surface, and the mixture burns. The chamber pressure rapidly increases along the vertical ab to p_3 , which is greater than the pressure created during fuel combustion in a usual engine. This is explained as follows.

First, heat outflow through chamber walls to the cooling system is reduced, because vapor is a poor heat conductor. Heat accumulates in combustion products, thereby increasing temperature and pressure.

Second, water decay products formed under the action of low-temperature plasma contain hydroxyl radicals (OH), which promote the combustion of carbon monoxide:



Moreover, carbon, which is usually liberated as soot particles, reacts with water vapor:



All these intensify combustion, and aid in complete combustion, and increase the efficiency of thermochemical conversion of energy.

Third, water vapor is a monatomic gas, which absorbs radiation energy in specific bands. The bands from $\lambda = 2.24$ to $\lambda = 3.27 \mu\text{m}$ and from $\lambda = 4.8$ to $\lambda = 8.5 \mu\text{m}$ are energetically important for water vapor [2]. According to the Planck law, radiation power in these wave ranges is maximal in the range from 1224 to 886 and from 603 to 341 K, respectively.

Fourth, the formed vapor occupies a definite volume of the combustion chamber, thereby reducing the space occupied by combustion products.

While the spark power required for ignition in IC engines strongly depends on mixture composition and pressure, ignition in our case is initiated with high stability and does not depend on these factors. As a result of normalization of the development of combustion process in the initial phase and reduction of its duration, ignition advance angle is decreased and thus there is an opportunity for preparing a more compressed mixture and reducing the counteraction of the piston to movement at the end of the compression stroke. Moreover, poor mixture limits within which engine operates stably are widened. This is helpful in regulating the engine power by a poor mixture, which is thermodynamically more advantageous than throttling.

The heat liberated during combustion acts on the liquid film. The liquid is rapidly heated to boiling point (f) and evaporates. The isobar segment fg represents vapor formation process under constant pressure p_3 and constant temperature T_S . The upper boundary curve ($x = 1$) separates the saturated vapor domain from the overheated vapor domain. Vapor at the point h is overheated to temperature T_O , which is greater than T_S .

Combustion products expand along the adiabat bc , whereas the overheated vapor expands along the adiabat $h\ell$ and pressure drops from p_3 to p_4 , doing useful work. Thereafter used-up gases (vertical cd) and vapors are removed from the engine. Thereafter in the intake stroke, a new liquid drop is injected between electrodes, a fresh fuel mixture is sucked in and compressed, and the whole process is repeated.

If the adiabat $h\ell$ intersects the boundary curve $x = 1$ above the point ℓ , for example, at n , then it will have a discontinuity because the adiabatic index k of overheated vapor is 1.3 [3] and 1.135 for saturated vapor. A discontinuity will also occur at the point m on the adiabat bc , and this slightly worsens the quality of engine operation. If vapors are heated such that the point n lies below the point ℓ , then heat losses increase through chamber walls owing to increased temperature jump at the chamber inner surface due to higher initial temperature of overheated vapors. Therefore, vapor overheating must take place such that the points n and ℓ coincide on the expansion segment.

The amount of heat liberated in combustion is

$$q_1 = c_v(T_3 - T_2), \quad (6)$$

which corresponds to the area $ABB'A'$, and the amount of heat outflow in the process cd is

$$q_2 = c_v(T_4 - T_1), \quad (7)$$

which is shown by the area $DCB'A'$.

Hence the thermal efficiency η_t is

$$\eta_t = 1 - \frac{q_2}{q_1} = 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3 - T_2)} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{T_4}{T_3} \frac{1 - \frac{T_1}{T_4}}{1 - \frac{T_2}{T_3}}, \quad (8)$$

where c_v is the specific heat capacity of combustion products under constant volume.

For the adiabat bc ,

$$\frac{T_3}{T_4} = \left(\frac{V_1 - V_\ell}{V_2 - V_h} \right)^{k-1} = \left(\frac{V_1}{V_2} \frac{1 - \frac{V_\ell}{V_1}}{1 - \frac{V_h}{V_2}} \right)^{k-1}, \quad (9)$$

where k is the adiabatic index.

Neglecting $\frac{V_\ell}{V_1}$ as quantity of higher smallness order compared to $\frac{V_h}{V_2}$ and since $\frac{V_1}{V_2}$ is the adiabatic compression ratio ε , we obtain

$$\frac{T_3}{T_4} = \varepsilon^{k-1} \left(\frac{1}{1 - \frac{V_h}{V_2}} \right)^{k-1}. \quad (10)$$

For the adiabat da ,

$$T_1 = T_2 \frac{(V_2)^{k-1}}{(V_1)^{k-1}}. \quad (11)$$

Thus we obtain

$$T_4 = T_3 \frac{(V_2 - V_h)^{k-1}}{(V_1)^{k-1}}. \quad (12)$$

Dividing Eq. (11) by expression (12), we obtain

$$\frac{T_1}{T_4} = \frac{T_2}{T_3} \frac{V_2^{k-1}}{(V_2 - V_h)^{k-1}} = \frac{T_2}{T_3} \left(\frac{1}{1 - \frac{V_h}{V_2}} \right)^{k-1}. \quad (13)$$

Substituting Eqs. (10) and (13) into formula (8), we obtain the expression for thermal efficiency

$$\eta_t = 1 - \frac{1}{\varepsilon^{k-1} \left(\frac{1}{1 - \frac{V_h}{V_2}} \right)^{k-1}} \times \frac{1 - \frac{T_2}{T_3} \left(\frac{1}{1 - \frac{V_h}{V_2}} \right)^{k-1}}{1 - \frac{T_2}{T_3}}. \quad (14)$$

For $\frac{V_h}{V_2} = \xi$, Eq. (14) takes the form

$$\eta_t = 1 - \frac{1}{\varepsilon^{k-1} \left(\frac{1}{1 - \xi} \right)^{k-1}} \times \frac{1 - \frac{T_2}{T_3} \left(\frac{1}{1 - \xi} \right)^{k-1}}{1 - \frac{T_2}{T_3}}, \quad (15)$$

where ξ is the volume coefficient of vapor content.

For $\xi = 0$, i.e., there is no vapor in the combustion chamber, we obtain the well-known formula for the thermal efficiency of an IC engine $\eta_t = 1 - \frac{1}{\varepsilon^{k-1}}$. The value of ξ increases with the volume of vapors in the combustion chamber, thereby increasing the thermal efficiency. Increased efficiency also results from increased compression ratio ε of the fuel mixture. The poorer the mixture, the higher the self-ignition point of the mixture and larger the compression ratio admitted by the mixture. While poor mixtures in usual IC engines are either badly ignited or do not ignite at all, this drawback is eliminated via combustion initiation by low-temperature plasma. The yield of nitrogen oxides and other harmful emissions is reduced with increasing air excess coefficient [4].

Since the vapor formation heat r decreases with temperature and consequently, pressure, the liquid drop must be heated to boiling point T_S as quickly as possible, spending an amount of heat q' . Overheating of vapors to temperature T_O (by overheating heat q_O) slightly increases the efficiency of vapor process.

Thus, the requirements for combustion control by low-temperature plasma can be formulated as follows: the energy liberated by the low-temperature plasma must split the liquid into parts in an optimal ratio in order to liberate maximal heat under minimal loss of heat through chamber walls during fuel combustion.

3. FORMULATION OF THE PROBLEM

Let the liquid particles flying to the inner surface of the combustion chamber form a heat-insulation film, whose surface at instant $\tau = 0$ is the initial surface, denoted by 0 in Fig. 3. Under the action of the heat of combustion products of temperature T_c , the film surface emits vapors, which form a liquid-solid interphase. At instant τ , the interphase is $x(\tau)$. The liquid layer of thickness $X_l(\tau)$ between boundaries 0 and I, evaporates into vapors, which form a layer of thickness $X_v(\tau)$ between boundaries I and II. At instant $\tau + d\tau$, liquid escapes from the layer $X_l(\tau + d\tau)$ denoted by boundaries 0 and I', and vapors occupy the space between boundaries I' and II', measured by

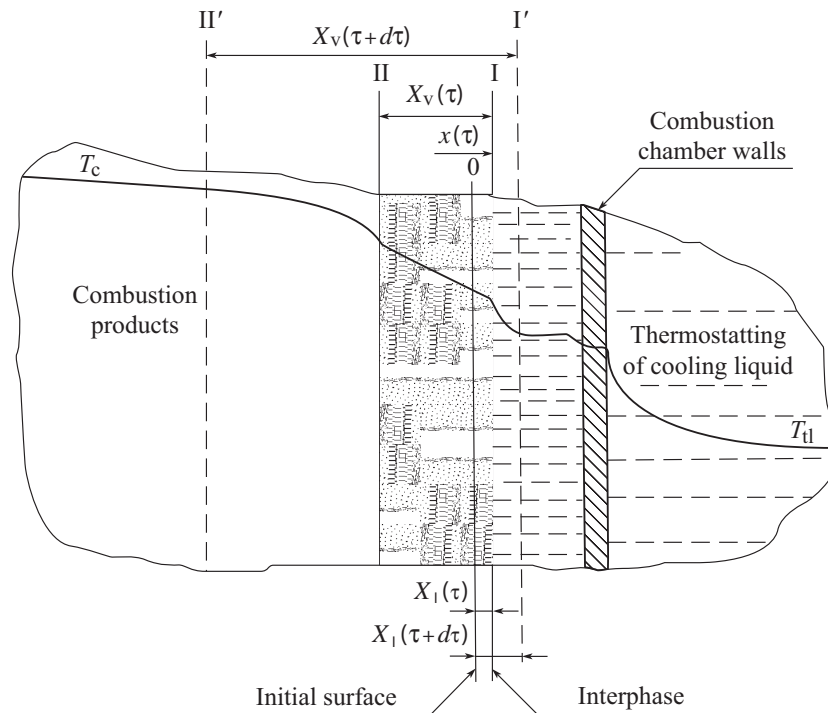


Fig. 3. Vapor formation scheme.

the quantity $X_v(\tau + d\tau)$. Cooling liquid of temperature T_{l1} flows along the outer surface of the combustion chamber walls. Our problem now is to find rate of displacement of the interphase and time of complete evaporation of the liquid phase, i.e., the heat-insulation film.

4. INTERPHASE: ITS DISPLACEMENT RATE

The quantity of heat per unit area in time $\Delta\tau$ that is spent in the zone of vapor formation front of thickness $\Delta\xi$ is

$$q_p \Delta\tau = \rho_k q \Delta\xi, \quad (16)$$

where ρ_k is the partial density of conversion components, kg/m^3 ; q_p is the specific thermal power of the front, W/m^2 .

Hence the specific thermal power of the front of conversion substances is

$$q_p = \rho_k q \frac{\Delta\xi}{\Delta\tau}. \quad (17)$$

For the energy characteristic of the conversion process, we can use the concept of the potential temperature of conversion, which is the potential energy of conversion of a substance

$$\Theta = \frac{\rho_k q}{\rho_c c_p}, \quad (18)$$

where Θ is conversion temperature, K; $\rho_c c_p$ is the volumetric heat capacity of the medium, $\frac{\text{J}}{\text{m}^3\text{K}}$.

Denoting the front displacement rate by $\frac{\Delta\xi}{\Delta\tau} = v$ and substituting (18) into (17), we obtain

$$q_p = v \rho_c c_p \Theta. \quad (19)$$

We assume that heat is supplied to the interphase surface via vapors from combustion products and escapes via the liquid layer and combustion chamber wall to the engine cooling system. Vapor formation heat is spent on converting liquid into vapor. The domain on the left of the interphase boundary consists of a vapor phase with characteristics ρ_v , c_v , λ_v , a_v , and the right side consists of a liquid phase with characteristics ρ_l , c_l , λ_l , a_l , where ρ_v and ρ_l denote the vapor and liquid density, respectively; c_v and c_l are the specific heat capacity of the vapor and liquid, respectively; λ_v and λ_l are the heat conduction coefficient of the vapor and liquid; and a_v , a_l are the thermal diffusivity of the vapor and liquid, respectively. Vapor temperature t_v and liquid temperature t_l must satisfy the equations

$$\frac{\partial^2 t_v}{\partial x_v^2} - \frac{1}{a_v} \frac{\partial t_v}{\partial \tau} = 0, \quad (20)$$

$$\frac{\partial^2 t_l}{\partial x_l^2} - \frac{1}{a_l} \frac{\partial t_l}{\partial \tau} = 0. \quad (21)$$

The interphase surface, which experiences the total pressure due to combustion products and vapors of temperature T_{prod} that is necessary for conversion of a substance from one phase into another, must satisfy the condition

$$t_v = T_{\text{prod}} = t_l. \quad (22)$$

To convert a substance from liquid state into vapor state, it must be supplied with a definite quantity of heat (energy) per unit mass $q \left(\frac{\text{J}}{\text{kg}} \right)$. Multiplying the latter by the density of the substance, we obtain the amount of heat $q_{\rho l}$ that is to be supplied per unit volume of the substance for converting it from the liquid phase into vapor state. The amount of heat required to move

the interphase surface through a distance dx is $q_{\rho l} \frac{dX_l}{d\tau}$ (specific thermal capacity of the front). Consequently,

$$\lambda_v \left(\frac{\partial t_v}{\partial x_v} \right) \Big|_{x_v=X} - \lambda_l \left(\frac{\partial t_l}{\partial x_l} \right) \Big|_{x_l=X_l} = q_{\rho l} \frac{dX_l}{d\tau}. \quad (23)$$

Applying the Neumann method [5], we obtain the solution of these equations

$$t_v - T_{\text{prod}} = (T_g - T_{\text{prod}}) + A \operatorname{erfc} \frac{x_v}{2\sqrt{a_v\tau}}, \quad (24)$$

$$t_l - T_{\text{prod}} = (T_{\text{cw}} - T_{\text{prod}}) + B \operatorname{erf} \frac{x_l}{2\sqrt{a_l\tau}}, \quad (25)$$

where A and B are constant coefficients and T_{cw} is the temperature of the chamber wall.

Since $x_v = X_v(\tau)$ and $x_l = X_l(\tau)$, we can rewrite Eqs. (24) and (25) as

$$-(T_{\text{prod}} - T_g) = A \operatorname{erfc} \frac{X_v}{2\sqrt{a_v\tau}}, \quad (26)$$

$$(T_{\text{prod}} - T_{\text{cw}}) = B \operatorname{erf} \frac{X_l}{2\sqrt{a_l\tau}}. \quad (27)$$

The solutions of Eqs. (26) and (27) must hold for all X_v and X_l . Therefore, they must be proportional to $\sqrt{\tau}$. Hence

$$X_l = k\sqrt{\tau} \quad (28)$$

and, by virtue of (16),

$$X_v = \beta k\sqrt{\tau}, \quad (29)$$

where k is a coefficient.

Substituting the solutions of Eqs. (24), (25), (28), and (29) into Eq. (23), we obtain

$$\frac{\lambda_v A}{\sqrt{\pi a_v}} e^{-\frac{\beta^2 k^2}{4a_v}} - \frac{\lambda_l B}{\sqrt{\pi a_l}} e^{-\frac{k^2}{4a_l}} = \frac{1}{2} q_{\rho l} k. \quad (30)$$

Equation (30), after substituting A and B from (26) and (27), takes the form

$$\frac{\lambda_v (T_g - T_{\text{prod}})}{\sqrt{\pi a_v} \operatorname{erfc}(\beta k/2\sqrt{a_v})} e^{-\frac{\beta^2 k^2}{4a_v}} - \frac{\lambda_l (T_{\text{prod}} - T_{\text{cw}})}{\sqrt{\pi a_l} \operatorname{erf}(k/2\sqrt{a_l})} e^{-\frac{k^2}{4a_l}} = \frac{1}{2} q_{\rho l} k. \quad (31)$$

Solving Eq. (31) numerically, we obtain k as a function of temperature. Figure 4 shows the temperature- and pressure-dependence of the coefficient k . The graphs show that k strongly depends on pressure, but weakly on temperature. Dividing Eq. (28) and (29) by τ , we obtain the rate v_l of displacement of the liquid-vapor interphase surface

$$v_l = \frac{k}{\sqrt{\tau}} \quad (32)$$

and the rate v_v of displacement of the surface of separation of vapors and combustion products

$$v_v = \frac{\beta k}{\sqrt{\tau}}. \quad (33)$$

Formulas (32) and (33) show that the boundary displacement rates are not constant, but decrease with time. Since in high-speed engines, the crankshaft rotates through 20° from the upper dead point in a very small time (the volume of the combustion chamber does not virtually change in this time), the pressure during combustion must steeply increase for the engine working process to be optimal. This will yield maximal k for high vapor production and ensure combustion almost

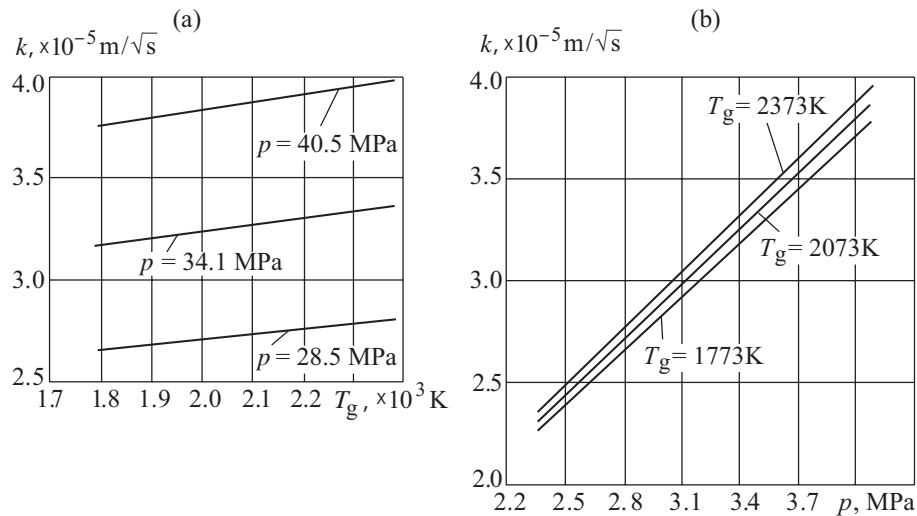


Fig. 4. Coefficient k versus temperature of combustion products (a) and combustion chamber pressure (b).

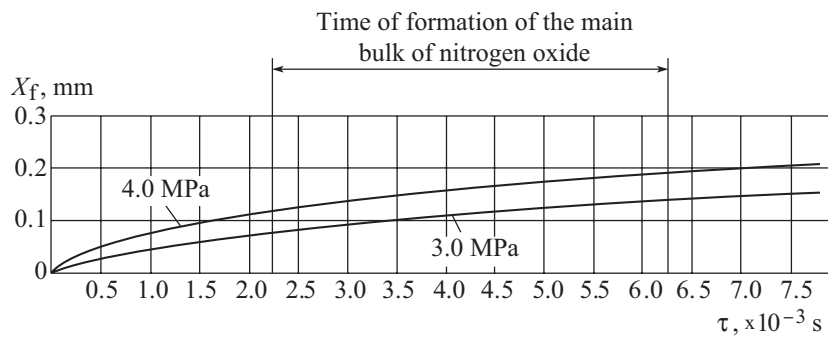


Fig. 5. Vapor film thickness versus time.

under constant volume, which is thermodynamically advantageous. Low-temperature plasma can initiate instantaneous (burst) combustion, called the detonation. In this case, flame propagates in the fuel mixture at supersonic speed along with the detonation wavefront. But detonation induced by low-temperature plasma is not harmful, which in ordinary IC engines is highly undesirable. Detonation happens in these engines spontaneously for several reasons and promotes, as a rule, premature pressure growth, which counteracts piston movement in the compression stroke, thereby resulting in increased overloads and overheating, i.e., abnormal engine operation. In our case, however, detonation is initiated in the plasma channel and promotes rapid combustion of even poor mixtures; consequently, low-octane fuel can be used and compression ratio and thereby the engine efficiency can be increased.

The formation of a heat-insulation vapor film reduces not only heat losses through combustion chamber walls, but also the formation of nitrogen oxides, which are formed in 2.2×10^{-3} – $6.2 \times 10^{-3} \text{ s}$ [6]. Figure 5 shows the time growth of the vapor film thickness. Initially, a sufficiently thick vapor film is formed, which envelops combustion products, whose interaction with relatively cold vapors reduces the rate of formation of nitrogen oxides, and ultimately suppresses this reaction.

When liquid completely evaporates from the combustion chamber inner wall, saturated water vapor is overheated. Since less energy is required for overheating water vapor, the coefficient k

increases from 2.3×10^{-3} (at saturation temperature) to $2.55 \times 10^{-3} \frac{\text{m}}{\sqrt{s}}$ (at 100° above the saturation temperature). During expansion, overheated vapors execute mechanical work in the working stroke.

Energy for plasma formation is assumed to be drawn from the internal energy of exhaust gases via conversion.

5. CONCLUSIONS

Control of combustion in IC engines by a low-temperature plasma combines the working processes in heat engines and steam machines into a single process. Therefore, the efficiency of an IC engine increases and fuel consumption and toxicity of exhaust gases are reduced. Moreover, the poor mixture limits in which an engine operates stably are widened. This is helpful in regulating the engine power through mixture dilution, which is thermodynamically more advantageous than fuel throttling. Widened ignition limits admits increased compression ratios and use of low-octane gasoline for high-revolution engines.

Low-temperature plasma can also be used to control mixture-formation and combustion process in diesel engines, in which work process proceeds along the same lines as the M -process [7].

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